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Title

- Electro-ribbon actuators and electro-origami robots

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Abstract:

Origami has inspired novel solutions across myriad fields from DNA synthesis to robotics. Even wider impact can be achieved by active origami, which can move and change shape independently. However, current active origami and the materials that power it are both limited in terms of strength, speed and strain. In this article, we introduce a new electrostatic active origami concept, electro-origami, which overcomes these limitations and allows for simple, inexpensive, lightweight, efficient, powerful and scalable electronic actuators and a new generation of lightweight and thin robots. The simplest embodiment of electro-origami, electro-ribbon actuators, can be easily fabricated from any combination of conducting and insulating material. We present electro-ribbon actuators that can lift 1000 times their own weight, contract by 99.8% of their length, and deliver specific energy and specific power equivalent to muscle. We demonstrate their versatility in high-stroke and high-force morphologies, multi-actuator lattices, 3D-printed and paper actuators, self-twisting spirals and tensile elements inspired by spider silk. More complex electro-origami devices include solenoids, adaptive grippers, robotic cilia, locomoting robots, self-packing deployable structures, origami artificial muscles and dynamic origami art.

Summary

Insulated conducting ribbons can be used to make powerful, versatile, ultra-thin actuators and smart origami structures.

MAIN TEXT

Introduction

Origami has been applied to multiple fields, including DNA synthesis (1), microfluidics (2), biomedical applications, electric batteries (3), robotics (4), manufacturing and space structures (5). Active origami, whereby independent motion is driven by internally generated forces, allows for even greater applicability, enabling self-deploying biomedical devices (6) and novel artificial muscles (7,8). Various actuation technologies can deliver forces for active origami (6–12), however the limitations of these actuation phenomena

have resulted in active origami structures that are either weak, slow to cycle, strain-limited or not made from thin materials. Here we introduce a new electrostatic active origami concept, which overcomes these limitations and delivers strong and dynamic electro-origami structures made from any combination of conducting and insulating materials.

Electrostatic forces have the potential to be extremely large: as Feynman eloquently put it, electric force is “about a billion-billion-billion-billion” times stronger than gravitational force (13). Actuators driven by electrostatic forces are characterized by high efficiencies, fast response times and low power requirements. Comb-drive actuators, for example, have been used for decades in MEMS devices (14), but the stroke of these actuators is in the order of micrometres (15). Larger displacements can be achieved through the use of zipping structures, whereby one electrode incrementally deforms towards a counter-electrode (16–18), however when these actuators have been built at the macro-scale, the forces they have been able to exert have been limited (19,20). Liquid-amplified electrostatic actuators have demonstrated high actuation forces, showing the potential of electrostatic zipping (21,22). In particular, hydraulically-amplified electrostatic actuators have used liquid-amplified electrostatic forces to deliver fluid pressure in flexible fluidic actuators (21,23), however when made into working devices their contractions are theoretically limited to less than 18% and their non-planar actuation prevents their use in origami structures (24). Electro-origami actuators are fundamentally different from these actuators, being driven by purely electrostatic forces with no hydraulic behaviour, requiring dramatically less liquid dielectric and no encapsulation, allowing for fast, simple fabrication and radically different actuating morphologies, and delivering contractions exceeding 99%.

Results

Electro-origami principle

The fundamental principle of electro-origami is an origami fold whose opposing sides are oppositely charged (Fig. 1A, S1A). At the fold hinge, a strong electric field is developed (Fig. S1B), and an electrostatic force is exerted. This electrostatic force is typically not great enough to do useful work or even cause visible movement. However, if a small bead of high-permittivity, high-breakdown-strength liquid dielectric is added at the hinge, it considerably amplifies the electrostatic force and causes the hinge to close (Fig. 1A–B, Movie S1), with the liquid dielectric being driven along as the hinge closes. The overall closing force is coupled to Maxwell pressure, $P \propto \epsilon E^2$, where ϵ is dielectric permittivity and E is the electric field (25). The liquid dielectric has two complementary effects: firstly, it increases closing force in proportion to its permittivity relative to air. Additionally, its breakdown strength is considerably higher than the breakdown strength of air. As such, the addition of liquid dielectric allows higher electric fields to be sustained because of its higher breakdown strength, greatly increasing maximum closing force by a factor of $\left(\frac{E_{\text{breakdown,liquid}}}{E_{\text{breakdown,air}}}\right)^2$. In this article, silicone oil was used as the liquid dielectric, whose permittivity and breakdown strength are roughly 2.7 and 6.7 times greater than air, implying maximum closing force could be increased up to 120-fold.

Serendipitously, as the electro-origami fold closes, the amplifying liquid dielectric bead is kept in place by dielectrophoretic forces (26), which have the effect of drawing high-permittivity materials (in this case the liquid dielectric) into regions of high electric field density (the electro-origami hinge) (27). In this way, a strong closing force is generated

throughout actuation using only a single bead of liquid dielectric, which greatly reduces device mass compared with fully submerged or encapsulated solutions (in experiments, a liquid bead provided 92% of the electrostatic force compared with a fully submerged system).

Modelling

We developed a mathematical model to investigate the effect of the bead of liquid dielectric upon the behaviour of this system (Supplementary Materials). For two parallel charged plates separated by an insulator and a medium (Fig. S2A), when the insulator is adhered to the insulator-adjacent electrode, the attractive force on the electrodes is given by

$$F = \frac{\frac{1}{2} \epsilon_{\text{medium}} \epsilon_0 A V^2}{\left(\frac{\epsilon_{\text{medium}}}{\epsilon_{\text{insulator}}} t_{\text{insulator}} + t_{\text{medium}} \right)^2}, \quad (1)$$

where F is the attractive force, ϵ_{medium} , ϵ_0 and $\epsilon_{\text{insulator}}$ are the permittivity of the medium, free space, and the insulator respectively, A is the plate area, V is applied voltage and $t_{\text{insulator}}$ and t_{medium} are the insulator and medium thickness respectively. If the insulator is thin compared to the medium ($t_{\text{insulator}} \ll t_{\text{medium}}$), the attractive force tends towards

$$F = \frac{\frac{1}{2} \epsilon_{\text{medium}} \epsilon_0 A V^2}{t_{\text{medium}}^2}, \quad (2)$$

which is equivalent to the attractive force between two parallel charged plates separated by a medium only. In contrast, if the medium is thin compared to the insulator ($t_{\text{medium}} \ll t_{\text{insulator}}$), the attractive force tends towards

$$F = \frac{\frac{1}{2} \epsilon_0 A V^2}{\epsilon_{\text{medium}} \left(\frac{t_{\text{insulator}}}{\epsilon_{\text{insulator}}} \right)^2}. \quad (3)$$

In the case of electro-origami, the medium (liquid dielectric or air) thickness ranges smoothly from zero at the fold hinge to considerably larger than the insulator thickness. Such a system cannot be solved analytically, so we developed a finite-element model of a zipping electro-origami fold based on Equation (1) and Euler-Bernoulli beam theory (Fig. S2B–C, Fig. S3, Supplementary Materials). The model confirms that only a small droplet of liquid dielectric is required to achieve considerable force amplification: a tiny bead of volume only 0.2 ml reduced pull-in voltage by over 80%, asymptotically approaching the fully submerged pull-in voltage of 1700 V (Fig. 1C, Supplementary Materials). Experimental results for an identical system (Fig. S1C) confirm the validity of the model (Fig. 1C).

Characterisation

Fundamentally, electro-origami allows high-strength zipping actuation of pre-folded origami structures, enabling a whole range of active origami designs. To characterise the actuation properties of the electro-origami concept in a working device, we begin with a simple practical embodiment, the electro-ribbon actuator (Fig. 1D), which comprises two electrodes and a single insulator. When voltage is applied to an electro-ribbon actuator, the opposing electrodes are charged and the actuator contracts (Fig. 1E). Electro-ribbon actuators can be easily fabricated using any combination of flexible insulating and flexible conductive material, including indium-tin-oxide (ITO) coated polyethylene terephthalate (PET), polyimide, graphene-loaded and pure polylactic acid (PLA) and pencil and office paper (Table S1).

Our standard actuator uses thin steel electrodes and polyvinyl chloride (PVC) tape (Fig. 1F). When electro-ribbon actuators contract fully, contraction approaches 100% because of their extremely low thickness when contracted (Fig. 1G, Movie S2). Actuation time is affected by applied voltage (Fig. S4A) and load (Fig. S4B): higher voltages sustain stronger fields, which increase the contraction speed of the actuator. Lighter loads decrease the electro-origami hinge angle, which similarly increases field strength, increasing contraction speed. Figs 2A–B show results from isometric testing of a standard electro-ribbon actuator (Fig. S4C shows the experimental setup); addition of a small bead (around 0.2 mL) of liquid dielectric at each electro-origami fold hinge dramatically increased contractile force by a factor of up to 37.

We demonstrated full-amplitude cyclic actuation at a bandwidth of 0.125 Hz (Fig. 2C, Movie S3). Higher frequency operation can be achieved if a lower amplitude stroke is acceptable: we demonstrated 5 Hz cyclic operation at 9.7% of full amplitude and 10 Hz cyclic operation at 0.62% of full amplitude (Fig. 2C). The charging time of electro-origami actuators is extremely fast and does not notably limit bandwidth; bandwidth limitation is dominated by mechanical inertia, adhesive and cohesive forces, and the availability of liquid dielectric. As suggested by the model (Fig. 1C), as long as a small quantity of liquid dielectric remains at the electro-origami fold hinge, performance is high. However, if all the liquid leaks away, performance is impaired. For long-term actuation, this can easily be addressed by adding features to retain the liquid dielectric between cycles. For example, we investigated surface structure modifications: perpendicular channel-shaped cut-outs in the insulator layer that act as liquid reservoirs. An actuator modified in this way delivered 100,000 isometric actuation cycles with negligible variation in force (Fig. 2D). After 100,000 cycles, the actuation force exerted was still roughly ten times greater than the force when no liquid dielectric was present.

Insulator charging can be an issue for zipping actuators, whereby charge can become trapped between cycles, however we did not observe any variation in performance during these 100,000 cycles that could be attributed to the effects of charging. One explanation for this is that the lower permittivity of the liquid dielectric (2.7) compared to the insulator (4.62) reduces the field sustained in the insulator layer. The efficiency of electrostatic actuators is typically high, in the region 60–90% (28); while this was not explicitly studied for electro-ribbon actuators, the highest recorded was 69.67% (Fig. 2E).

The morphology of electro-ribbon actuators presents a large design space. Figures 2G–I show the effect of varying the dimensions of a electro-ribbon actuator's two electrodes. Since electro-ribbon actuators are composed of a pair of steel electrodes, which are deflected by an external load, they act as tension springs, exerting a tensile force that

monotonically increases with extension. The effect of electrode dimension upon stroke and load is tied to their bending stiffness, which is influenced by thickness, length and width according to beam theory. Increasing electrode thickness and width increase the second moment of area of the beam, which increases its flexural rigidity EI , where E is Young's Modulus and I is second moment of area. Reducing the beam length reduces the moment induced by loading, reducing deflection. As such, stiffer, shorter beams tend to deflect less under load (reducing available stroke), and the reduced deflection implies a stronger electric field and accordingly larger electrostatic force. Results from simulation of the effect of electrode morphology for a single electro-origami fold (Fig. S5B–D) show qualitative agreement with Figures 2G–I, with the same relationships between thickness, length and width and stroke and load observed.

By investigating the effects of electrode dimension upon output parameters, we gained an understanding for how specific performance characteristics could be increased. Using these findings, we created a high-stress actuator that achieved a maximum actuation stress of 40.76 kPa. Despite lifting 527.75 g, over 500 times its mass, contraction remained high at 33.91%. Fig. 3A and Movie S4A show a similar high-stress actuator lifting 410 g. A high-specific-force actuator could lift 373 g, over 1000 times its mass, while contracting by 17.05%. We created a high-stroke, high-contraction actuator that achieved a stroke of 181.92 mm (Fig. 3B, Movie S4B), shortening by an impressive 99.84%. This is the highest contraction we are aware of for contracting actuated structures. The highest recorded average contraction rate was $1161\% \text{ s}^{-1}$ and peak contraction rate $1985\% \text{ s}^{-1}$. The highest recorded specific energy was 6.88 J kg^{-1} and specific power 103.51 W kg^{-1} (Fig. 2F, Movie S5), similar to the performance of mammalian muscle (typical 8 J kg^{-1} and 50 W kg^{-1}) (29). The highest recorded energy density was 44.17 kJ m^{-3} and power density 853.83 kW m^{-3} . These performance characteristics are summarised in Table 1, which also provides structural properties of the electro-ribbon actuators in question.

In comparison with typical performance characteristics for selected previously investigated electroactive actuator structures, electro-origami delivers stress of the order of muscle (muscle 0.1 MPa, HASEL 0.032 - 0.3 MPa (23), dielectric elastomer 1.6 MPa (29), Peano-HASEL 6 MPa (24)), considerably higher contraction than all previous technology (Peano-HASEL 10%, muscle 20%, multilayer dielectric elastomer 46% (30)), similar specific energy to muscle (muscle 8 J kg^{-1} , HASEL 70 J kg^{-1} , dielectric elastomer 150 J kg^{-1}) and similar order specific power to all previous technology (muscle 50 W kg^{-1} , Peano-HASEL 160 W kg^{-1} , dielectric elastomer 500 W kg^{-1}).

Electro-origami materials

We initially investigated PET, polyimide tape and PVC tape as insulators in an electro-origami fold test rig and confirmed that insulators with higher permittivities implied greater electrostatic forces (Fig. S6), consistent with Equation 1. Nonetheless, because of the simplicity of the electro-origami concept, any combination of conductive and insulating material can be used to manufacture useful devices. We cut strips of commercially available ITO-coated PET sheet and attached them together using cyanoacrylate adhesive to make an electro-ribbon actuator in minutes (Fig. 3C, Movie S6A). 3D-printed electro-origami is also easily fabricated; we made an electro-ribbon actuator from 3D-printed graphene-loaded PLA and a 3D-printed pure PLA insulator (Fig. 3D, Movie S6B). The insulator was a single 0.4 mm-thick 3D-printed layer of standard PLA filament that, once soaked in liquid dielectric, could withstand 10 kV. It is even possible to manufacture electro-origami devices using household or office materials. We

used a normal HB pencil to draw graphite electrodes onto standard photocopier paper and joined the two layers together using cyanoacrylate adhesive to make a pencil–paper electro-ribbon actuator. After soaking in silicone oil, the 2 g paper actuator could lift 3 g through a stroke of 45 mm (Fig. 3E, Movie S6C).

Electro-origami structures

Electro-ribbon actuators can also be easily integrated within multi-actuator structures to deliver higher forces and strokes. Stroke can be improved by stacking multiple actuators in series (Fig. 4A, Movie S7A), while force can be increased using a parallel arrangement (Fig. 4B, Movie S7B). A lattice containing both series and parallel actuator elements allows for a balance between improved stroke and force (Fig. 4C, Movie S7C). Bulk repetition of lattice structures will allow for the manufacture of self-actuating meta-materials powered by electro-origami across multiple scales.

While the structures presented so far require external load to prime them for actuation, it is straightforward to manufacture pre-bent electro-ribbon actuators that do not require pre-loading (Fig. 5A, Movie S8A). The electro-origami concept can be further extended to a wide range of electro-origami actuators. Fig. 5B shows an electro-origami spiral, which consists of two insulated electrodes wrapped around an acrylic cylinder. When actuated, they wrap around one another, creating a tightly bound spiral of alternating electrodes (Movie S8B). This arrangement can be used to make simple torsional actuators. An alternative arrangement of this structure takes inspiration from the tension-maintaining behavior of spider silk: we made an electro-origami spiral constrained at one electrode tip which spools around a central cylinder in the same way that spider silk spools around liquid droplets (31), resulting in a large stroke of over 60 cm (Fig. 5C, Movie S8C). The maximum stroke of this design is only limited by electrode length.

Fig. 6A–E demonstrates the versatility of the electro-origami concept. Using a single origami design featuring three electrodes in series (Fig. 6A), we were able to make four unique functional devices (Movie S9) with origami folds and clips to hold the folds in place. First, we folded the design into a solenoid-like (self-restoring, linearly moving) actuator (Fig. 6B, Movie S9A). The same design could be folded into an electro-origami adaptive gripper (Fig. 6C, Movie S9B). Upon actuation the gripper arms close around the object to be gripped, with electro-adhesive forces also improving grip strength, as in previously demonstrated electro-adhesive dielectric elastomer grippers (32). More complex motions are achievable by charging electrodes sequentially: by attaching a beam to the same design we were able to replicate the motion of a biological cilium, complete with a power and recovery stroke (Fig. 6D, Movie S9C). Finally, still using the same origami design we were able to fold an electro-origami robot: sequential electrode activation in one direction moves the robot to the right, while reversing the sequence moves the robot to the left (Fig. 6E, Movie S9D).

Figures 6F–G further show electro-origami’s potential real-world functionality. An electro-origami fan can be easily made from a flat rectangular sheet with alternating electrodes. Alternating mountain and valley folds transform the sheet into a concertina shape, which may be pinched one end to produce a fan that closes when activated (Fig. 6F, Movie S10A). This design could be used to create self-packing solar panels for space

applications, with origami folding allowing compact packing as is achieved by tree leaves when packed inside buds (33). Fig. 6G shows an electro-origami muscle, made by alternately folding two insulated electrodes over one another. This artificial muscle exhibited over 50% contraction (Movie S10B), shortening by over 4 cm in less than a second. Electro-origami artificial muscles could be used to replace or augment biological muscle in humanoid robots, prosthetics and wearable devices.

Finally, an origami crane was fabricated from polyimide film and painted with conducting ink electrodes on its wings and inside its body. Activation causes wing flexion resulting in a flapping motion (Fig. 6H, Movie S10C). Combined with printable conductive inks, the electro-origami concept will allow inkjet-printed origami patterns that can be folded into functional devices.

Discussion

Electro-origami is a new actuation concept that exploits electrostatic attraction, high-permittivity, high-breakdown-strength insulating fluids and dielectrophoresis to deliver powerful, versatile actuators and robotic devices. While the number of active designs that electro-origami enables is very large, it is limited by the progressive zipping nature of the electro-origami concept – active devices that lack an origami fold to initiate zipping cannot be directly actuated. For these devices, discrete electro-origami actuators could be included to achieve motion. Another limitation of electro-origami is the high voltage required to develop strong electric fields. As with other state-of-the-art high field actuators (23,24,29), an amplifier is needed to supply high voltage, which may introduce safety concerns for some applications. Nonetheless, the performance and versatility demonstrated here highlights the suitability of the electro-origami concept to a wide range of fields, including robotics, engineering, and transportation, for applications such as deployable structures, space systems, and multi-degree-of-freedom prostheses and robots.

Materials and Methods

Manufacture of electro-origami folds. Fig. S1A shows one way of making an electro-origami fold:

1. The electrodes and insulator are prepared. Wires can be soldered to the electrodes so that voltage can be applied. The insulator should be larger than the electrodes in the non-thickness directions to fully encapsulate it.
2. The electrodes are insulated using an insulator material, which also serves as the origami material to be folded. The figure shows insulation of the electrodes on both sides. In this case, the tape fully encapsulates the electrode to ensure no arcing will occur. It is possible to insulate on the inner surface of the origami fold only, however in this case it should be especially large in the non-thickness directions to prevent arcing around it.
3. The electro-origami is folded to prepare it for actuation.

Full submersion experiment. As part of the electro-origami concept, a small bead of liquid dielectric is added at the origami hinge, which considerably increases electrostatic force due to its higher breakdown strength and permittivity. A similar increase in tensile force could be achieved by submerging the whole device in liquid dielectric, but this would considerably increase mass and slow down movement due to opposing viscous and hydraulic forces. The liquid bead, in contrast, negligibly alters device mass and behaviour but greatly increases force. We compared the difference in isometric tensile force between

a fully submerged electro-ribbon actuator and one with only a bead of liquid dielectric at each origami hinge. The non-submerged actuator delivered 91.61% of the force of the submerged actuator, confirming the effectiveness of the electro-origami concept.

Electro-origami field strength distribution. The field strength distribution of electro-ribbon actuators is highly concentrated near the origami hinge. Fig. S1B shows results from simulation using a field-modelling software (QuickField, Tera Analysis Ltd., Denmark). The conductors are 30 mm long and the actuator is submerged in a medium with permittivity 2.7, matching the silicone oil used in most experiments. The PVC tape permittivity is 4.62. The voltage between the upper and lower electrodes is 10 kV.

Derivation of electrostatic attractive force between two plates separated by an insulator and a medium. In electro-origami, an electrode and counter-electrode form a zipping structure. Between the electrodes is an insulator (which prevents short-circuit) and a medium (which may be air or high-permittivity liquid dielectric). To shed light on the behaviour of this system, we performed from-first-principles electrical analysis on an analogous system.

Consider two plates separated by two dielectric slabs of thicknesses $t_{insulator}$ and t_{medium} and permittivities $\epsilon_{insulator}$ and ϵ_{medium} (Fig. S2A). They may be modelled as two variable capacitors in series whose capacitances are $C_{insulator}$ and C_{medium} . When a voltage V is applied across the two plates, they become charged. A virtual, infinitely thin plate at a voltage $V_{interface}$ may be assumed between the two dielectric slabs, where $V_{interface}$ is greater than zero but lower than V . The charge separated across the insulator dielectric slab, $Q_{insulator}$, is described by

$$Q_{insulator} = C_{insulator}V_{interface}. \quad (4)$$

The charge separated across the medium dielectric slab, Q_{medium} , is described by

$$Q_{medium} = C_{medium}(V - V_{interface}). \quad (5)$$

Since the slabs are modelled as two capacitors in series, their charges are equivalent:

$$Q_{insulator} = Q_{medium}, \quad (6)$$

$$\therefore C_{insulator}V_{interface} = C_{medium}(V - V_{interface}), \quad (7)$$

$$\therefore V_{interface} = \frac{C_{medium}}{C_{insulator} + C_{medium}} V, \quad (8)$$

The capacitance of the insulator and medium dielectric slabs are described by

$$C_{insulator} = \frac{\epsilon_{insulator}\epsilon_0 A}{t_{insulator}} \quad (9)$$

and

$$C_{medium} = \frac{\epsilon_{medium}\epsilon_0 A}{t_{medium}} \quad (10)$$

respectively. Substituting these into Equation 8 leads to

$$V_{interface} = \frac{\epsilon_{medium} t_{insulator}}{\epsilon_{insulator} t_{medium} + \epsilon_{medium} t_{insulator}} V. \quad (11)$$

The energy $E_{insulator}$ stored across in insulator slab is given by

$$E_{insulator} = \frac{1}{2} \frac{\epsilon_{insulator} \epsilon_0 A V_{interface}^2}{t_{insulator}}. \quad (12)$$

Differentiation of $E_{insulator}$ with respect to $t_{insulator}$ gives the force $F_{insulator}$ exerted at the interface.

$$F_{insulator} = -\frac{1}{2} \frac{\epsilon_{insulator} \epsilon_0 A V_{interface}^2}{t_{insulator}^2}. \quad (13)$$

Substituting Equation 11 results in

$$F_{insulator} = -\frac{1}{2} \frac{\epsilon_{insulator} \epsilon_0 A V^2}{\left(\frac{\epsilon_{insulator}}{\epsilon_{medium}} t_{medium} + t_{insulator} \right)^2}. \quad (14)$$

An equal and opposite force is felt by the lower plate. Similarly, for the medium slab, the force F_{medium} exerted at the interface is

$$F_{medium} = \frac{1}{2} \frac{\epsilon_{medium} \epsilon_0 A (V - V_{interface})^2}{t_{medium}^2}. \quad (15)$$

Substituting Equation 11 results in

$$F_{medium} = \frac{1}{2} \frac{\epsilon_{medium} \epsilon_0 A V^2}{\left(\frac{\epsilon_{medium}}{\epsilon_{insulator}} t_{insulator} + t_{medium} \right)^2}. \quad (16)$$

Unless the insulator and medium have the same permittivity, the forces exerted at the plates differ: the plate beside the material with the lower permittivity will experience a greater force. However, this does not imply that a net force acts to move the system through space; the resultant force acting on the plates is matched by an equal and opposite resultant force acting on the interface between the two dielectric slabs:

$$F_{interface} = F_{insulator} + F_{medium} = \frac{1}{2} \frac{\epsilon_{medium} \epsilon_{insulator} (\epsilon_{insulator} - \epsilon_{medium}) \epsilon_0 A V^2}{(\epsilon_{insulator} t_{medium} + \epsilon_{medium} t_{insulator})^2}. \quad (17)$$

In the case of electro-origami, the insulator is solid and firmly attached by adhesive to the insulator-adjacent plate, while the medium is liquid. As such, we assume the insulator and insulator-adjacent plate are inseparable and that the insulator is considerably stiffer than the (liquid) medium, such that its compression by $F_{insulator}$ is negligible, and it transmits any forces felt directly to the insulator-adjacent plate. This implies that the medium force F_{medium} will be exerted upon both plates. As such, the attractive force between the two plates is equal to F_{medium} :

$$F = \frac{1}{2} \frac{\epsilon_{medium} \epsilon_0 A V^2}{\left(\frac{\epsilon_{medium}}{\epsilon_{insulator}} t_{insulator} + t_{medium} \right)^2}. \quad (1)$$

Experimental validation of droplet volume model. We performed experiments to confirm the validity of the Euler-Bernoulli beam theory droplet volume model. An exact quantity of liquid dielectric was added by micropipette to an electro-origami fold hinge matching the one simulated by the model (Fig. S1C). Applied voltage was gradually increased until pull-in occurred, and this pull-in voltage was recorded. Results show good agreement with those of the model (Fig. 1C).

Manufacture of electro-ribbon actuators. Fig. 1F shows one way of making an electro-ribbon actuator:

1. The electrodes and insulator are prepared. Wires can be soldered to the electrodes so that voltage can be applied. The insulator should be larger than the electrodes in the non-thickness directions to fully encapsulate it.
2. One or both electrodes are insulated using the insulator material. The figure shows insulation of the upper electrode on both sides. In this case, the tape fully encapsulates the electrode to ensure no arcing will occur. It is also possible to insulate both electrodes. Alternatively, insulation can consist of only the central insulating layer, however in this case it should be especially large in the non-thickness directions to prevent arcing around it.
3. Connections at the ends of the actuator are made to create two origami hinges and hold the actuator together under high load. Connections can be made using any connection method such as adhesive, magnetic or mechanical. During experiments, we used cyanoacrylate or epoxy adhesive, single magnets (since some electrodes were magnetic), magnet pairs or mechanical clips including insulated bulldog clips or custom acrylic clips held in place by plastic nuts and bolts.
4. The actuator is complete and can be extended by application of a central load. A liquid dielectric bead may be added at each origami hinge, and application of high voltage will cause exertion of force and contraction.

Reported electro-ribbon actuators. In the main text, we avoid describing the specifications of example actuators in detail for reasons of brevity, and instead refer to example actuators based upon their qualities, for example the “standard” and the “high-stress” electro-ribbon actuator. These actuators are made from of steel strips insulated with PVC tape. The dimensions of the steel strips used to fabricate them, along with their masses, contractions and descriptions, are shown in Table 1.

Test protocol for isometric and isotonic experiments. During isometric testing, an electronic ribbon actuator was held at various actuator extensions (Fig. S4C). The upper central point of the actuator was attached to a load cell (DBCR-10N-002-000, Applied Measurements Ltd., UK), which was attached to a rigid frame. The lower central point of the actuator was attached to a precision jack stand, which could be used to adjust actuator extension. Extension was recorded using a laser displacement meter (LK-G402, Keyence, Japan), which measured the displacement of the top of the jack stand. Application of high voltage caused electrostatic attraction and zipping, resulting in a tensile force at the centre of the actuator, which was measured by the load cell. Liquid dielectric was added by pipette to the actuator's origami hinges.

During isotonic testing, the upper central point of the actuator was attached to a rigid frame (Fig. S4C). A known mass was attached to the lower central point of the actuator, exerting a constant vertical load and causing actuator extension. Actuator contraction was recorded using a laser displacement meter, which measured the displacement of the test mass. For each trial, liquid dielectric was added by pipette to the actuator's origami hinges, and high voltage was applied until actuation was completed.

Variation between samples of standard electro-ribbon actuator. To investigate variation between actuator samples, we fabricated five standard electro-ribbon actuators and performed isometric tests at actuator extensions of 1, 2 and 4 mm. Fig. S4D–E shows tensile force variation with voltage and extension: points are averages of 5 trials of five samples (25 total trials) and error bars show \pm one standard deviation between averages of five trials for each sample (5 samples). Maximum standard deviation for liquid dielectric data was 0.2475 N at 6 kV.

Bandwidth testing. We performed bandwidth testing to determine the frequencies of operation that electro-origami could deliver. A standard electro-ribbon actuator (Table S2) was modified by the addition of a small mechanical stop. This stop slightly reduced the maximum contraction but limited the adhesive and cohesive forces associated with the liquid dielectric when the actuator fully closed, allowing for higher frequency repeating operation. At a voltage of 7 kV, this actuator was capable of full actuation and relaxation at a bandwidth of 0.125 Hz. If full contraction is not required, such that lower stroke is allowed, and bandwidth is less influenced by adhesive and cohesive forces, much higher bandwidths can be achieved; 5 and 10 Hz are demonstrated using 7 kV (Fig. 2C, Movie S3).

Cyclic testing. Cyclic testing was performed to determine the effects of long-term continuous reciprocating use of electro-origami devices. A 30 mm long, 12.7 mm wide electro-ribbon actuator with 50 μ m thick electrodes was modified with multiple parallel channel-shaped cut-outs in the insulator layer, aligned perpendicular to actuator's long axis, which acted as liquid reservoirs to retain liquid dielectric during the cyclic experiment. The actuator was stimulated with a 50% duty cycle square voltage wave of amplitude 8 kV at a frequency of 4 Hz. There was negligible variation in isometric force over 100,000 cycles (Fig. 2D), and after 100,000 cycles the force exerted was 8.706 times greater than the force exerted by the same actuator with no liquid dielectric present. This demonstrates how features such as surface structure modifications can be used to ensure retention of liquid dielectric for long-term operation of electro-origami devices. Surface structure (including surface roughness) can affect the behaviour of the liquid dielectric and

the electric field generated, and as such can impact the behaviour of electro-origami devices.

Measurement of energetic efficiency. To measure energy efficiency, we used data recorded from experiments. The high voltage amplifiers used (5HVA24-BP1, UltraVolt, United States) provided monitor voltage outputs corresponding to delivered high voltage and current. These monitor voltages were recorded using a data acquisition device (NI USB-6343, National Instruments, United States) and converted to units of volts and amperes. The product of the inferred voltage and current was the electrical power. To determine electrical energy consumed, electrical power was numerically integrated using the MATLAB “trapz” function as an actuator lifted a load. Since the voltage when the actuator was relaxing was zero, the power was also zero at this time and only the electrical power when the actuator was shortening was considered. Mechanical energy output was calculated according to gravitational potential energy, i.e. $GPE = mgh$, where GPE is gravitational potential energy, m is mass, g is local acceleration due to gravity and h is stroke. Efficiency was calculated as mechanical energy output divided by electrical energy consumed.

Efficiency varied between experiments and the greatest variation was a function of which insulation was used. For example, PVC tape, which has a comparatively low resistance (10^{12} – 10^{14} Ωm), resulted in a noticeable leakage current, which consumed electrical energy without providing any mechanical energy, resulting in lower efficiencies. Using PVC insulation, maximum leakage current when 6 kV was applied was 21.74 μA implying a leakage current per unit area of 17.12 mA m^{-2} (electrode dimensions were 100 by 12.7 mm). In contrast, in experiments where polyimide tape was used (resistance in the order of 10^{15} Ωm), maximum leakage current was around 0.2 μA , implying a leakage current per unit area of 0.16 mA m^{-2} . As such, less energy was lost to leakage, and efficiency was considerably higher. The trial with the greatest efficiency involved a standard electro-origami actuator, insulated with two layers of polyimide tape, lifting a 3 g mass while actuated by an applied voltage of 6 kV. The stroke was 51.7 mm implying an output mechanical energy of 1.5215 mJ. The electrical energy consumed calculated using the MATLAB “trapz” function was 2.1839 mJ. Therefore, the efficiency was calculated as 69.67%. Fig. 2E shows applied voltage, delivered current, and electrical power traces during the experiment in question.

Simulating the effect of morphology upon output parameter. Euler-Bernoulli beam theory becomes less accurate as deflections increase. The developed MATLAB model can be used with larger tip loads that induce greater deflections, however the diminishing accuracy of results as tip load increases should be considered. Nonetheless, results can provide qualitative support for experimental findings. The developed model was used to investigate the effect of morphology (electrode thickness, length and width) upon output parameters (maximum load lifted and maximum stroke), for comparison with experimental results (Fig. 2G–I). The simulated electrode had the following standard properties thickness 50 μm , length 100 mm, width 12.7 mm and Young’s Modulus 190 GPa (matching those of the standard electro-ribbon actuator). The results (Fig. S5B–D) show qualitative agreement with those from experiments, exhibiting the same relationships between thickness, length and width and load and stroke.

Calculation of performance characteristics for electro-ribbon actuators. Actuator thickness was calculated assuming two electrodes (using steel strip thickness) and one

insulator, the insulator being comprised of two layers of PVC tape. This was the number of layers used to make most actuators (the insulator could have been comprised of a single layer of PVC tape, however would not be able to withstand 10 kV). Similarly, actuator mass was the combined mass of the conductors and insulator. Detailed characteristics of the electro-ribbon actuators in question are available in Table 1.

Actuator force was determined differently depending on the type of experiment. For isotonic experiments, actuator force was the weight of the load lifted. For isometric experiments, actuator force was recorded using a load cell (DBCR-10N-002-000, Applied Measurements Ltd., UK). Maximum achieved actuator force was 12.91 N using the high-force actuator, which lifted 1.316 kg.

Stress was calculated as actuator force divided by maximum actuator cross sectional area, which was steel strip free length multiplied by steel strip width. The highest achieved stress was achieved with an actuator of length 10 mm and width 12.7 mm, implying a maximum cross-sectional area of 127 mm². This actuator lifted a maximum load of 527.75 g, implying a force of 5.1772 N. These imply a stress of 40.77 kPa.

Specific force was calculated as actuator force divided by actuator mass. The highest achieved specific force was 10164.25 N kg⁻¹ using the high-specific-force actuator, which lifted 373 g despite having a mass of only 0.36 g, lifting over 1036 times its own mass.

Stroke was the distance travelled during actuation, typically recorded using a laser displacement meter (LK-G402, Keyence, Japan). Contraction was calculated as stroke divided by initial actuator length, which was equal to stroke divided by the sum of stroke and actuator thickness. The highest achieved contraction was achieved by an actuator featuring from 20 µm thick electrodes, implying an actuator thickness of 300 µm (Two 20 µm thick electrodes and two 130 µm thick insulator layers). The stroke was 181.92 mm, implying an initial actuator length of 182.22 mm. This implied a contraction of 99.84%.

Contraction rate was calculated as actuator speed divided by initial actuator length. The highest recorded contraction rates were achieved during power-measurement experiments (Fig. 2F, Movie S5). As the mass travelled upwards, it travelled 5.0869 mm in 0.073 s, implying an average speed of 69.6835 mm s⁻¹. The actuator's initial length was 6 mm, implying an average contraction rate of 1161% s⁻¹. The actuator's peak speed as the mass travelled upwards was 119.1121 mm s⁻¹, implying a peak contraction rate of 1985% s⁻¹.

Stroke mechanical energy was calculated as the change in gravitational potential energy associated with stroke, equal to the product of mass, stroke and local gravitational acceleration.

Power was calculated as the sum of the time derivatives of potential energy and kinetic energy. The time derivative of potential energy was calculated as $\frac{d}{dt}(mgh) = mgv$, where m was mass, g was local acceleration due to gravity, h was mass position and v was mass velocity. The time derivative of kinetic energy was calculated as $\frac{d}{dt}\left(\frac{1}{2}mv^2\right) = mva$, where a was mass acceleration. As such, power was calculated as $mgv + mva$.

Specific energy was calculated as stroke mechanical energy divided by actuator mass and specific power was calculated as power divided by actuator mass. The highest achieved

specific energy was achieved by an actuator of mass 2.28 g, which lifted a 27.75 g load through a stroke of 57.63 mm, implying a stroke mechanical energy of 15.6885 mJ, which implies a specific energy of 6.8809 J kg⁻¹. The highest achieved specific power was achieved by an actuator of mass 13.2 g, which oscillated a 1033 g mass at a frequency of 6.9 Hz (Fig. 2F, Movie S5). The average and peak power were 0.6792 W and 1.3663 W, implying average and peak specific powers of 51.45 and 103.51 W kg⁻¹ respectively.

Energy density was calculated as stroke mechanical energy divided by actuator volume. Power density was calculated as power divided by actuator volume. The highest achieved energy density was achieved with an actuator of length 10 mm and width 12.7 mm, featuring two 50 µm thick electrodes and two layers of 130 µm thick insulator, implying a volume of 45.72 mm³. This actuator lifted a 257.3 g load through a stroke of 0.8 mm, implying a stroke mechanical energy of 2.0193 mJ, which implies an energy density of 44.17 kJ m⁻³. The highest power density was achieved by the same actuator with the highest achieved specific power, which had length 100 mm, width 12.7 mm and featured two 500 µm thick electrodes and two layers of 130 µm thick insulator, implying a volume of 1600.2 mm³. The average and peak power were 0.6792 W and 1.3663 W, implying average and peak power densities of 424.45 kW m⁻³ and 853.83 kW m⁻³ respectively.

The dimensions, masses and contractions of actuators achieving maximum performance characteristics are presented in Table 1. In general, long actuators with thin electrodes were more compliant and deflected further under load, implying high strokes. In contrast, short actuators with thick electrodes were stiffer and deflected less under load, implying increased electric fields and consequently greater forces. To maximise actuation stress, short actuators were also advantageous because they maximised the amount of “active” actuator area; in long actuators that progressively zip, only a small fraction of the actuator area is contributing a large electrostatic force. For performance metrics that are a function of both force and stroke, such as specific energy and power density, intermediate values of actuator length and thickness resulted in the best performance.

Insulator material investigation using an electro-origami fold test rig. We investigated the electro-origami concept using a simple test rig (Fig. S1C). The test rig consisted of an upper electrode (a 70 µm thick, 12.7 mm wide steel strip) that was attached with adhesive to an acrylic plate. The upper electrode was insulated using one of several insulator materials. A second electrode (a 70 µm thick, 12.7 mm wide, steel strip with free length 100 mm) was fixed at one end adjacent to the insulated electrode. Application of a test mass to the tip of the second electrode caused cantilever deflection. Application of a bead of liquid dielectric and high voltage caused electrostatic zipping, raising the test mass against gravity.

We investigated the maximum load lifted with the insulator being either polyethylene terephthalate (PET), polyimide tape or PVC tape. The permittivity of PET is typically stated as between 3 and 3.4, polyimide tape between 3.4 and 3.5, and the PVC tape used had a permittivity of 4.62 (personal communication, Advance Tapes). The thickness of the insulator layer was conserved and the dominant contributor to flexural rigidity was the steel electrode, so behaviour was purely a function of electrical properties. Results showed that maximum load lifted increased monotonically with insulator permittivity (Fig. S6C–D), as predicted by Equation S14.

Multi-actuator structures. The standard electro-ribbon actuator could lift a 26 g mass 57.63 mm. Two standard electro-ribbon actuators in series could lift a 22 g mass 109.90 mm. Two standard electro-ribbon actuators in parallel could lift a 38 g mass 67.42 mm. The lattice of standard electro-ribbon actuators could lift a 26 g mass 107.24 mm.

Supplementary Materials

Materials and Methods

Fig. S1. Manufacture, field strength distribution and experimental test setup of electro-origami fold.

Fig. S2. Models used to derive electrostatic force.

Fig. S3. Flowchart showing structure of a recursive MATLAB script.

Fig. S4. Characterisation and analysis of electro-ribbon actuator.

Fig. S5. Results from electro-origami fold simulation.

Fig. S6. Effect of material properties on performance of electro-origami fold.

Table S1. Summary of materials used for electro-origami.

Movie S1. An electro-origami fold.

Movie S2. Isotonic and isometric actuation of a standard electro-ribbon actuator.

Movie S3. Bandwidth testing of a standard electro-ribbon actuator.

Movie S4. High-stress and high-contraction electro-ribbon actuators.

Movie S5. High-power electro-ribbon actuator.

Movie S6. Manufacture and testing of electro-ribbon actuators made from different materials.

Movie S7. Series, parallel and lattice arrangements of standard electro-ribbon actuators.

Movie S8. Electro-origami actuators.

Movie S9. Four electro-origami devices from one electro-origami design.

Movie S10. Complex electro-origami devices.

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Data and materials availability: All data needed to evaluate the conclusions in the paper are present in the paper or the Supplementary Materials. The datasets generated and analysed during the current study are available in the University of Bristol Research Data Repository (<https://data.bris.ac.uk/data/>) [full DOI to be provided before publication].

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Fig. 1. Electro-origami and electro-ribbon actuator concept. (A), Diagram of actuated electro-origami fold, with charge distribution. (B), Photograph of actuated electro-origami fold. (C), Effect of droplet volume on pull-in voltage for a zipping electro-origami fold. (D), Diagram of electro-ribbon actuator. (E), Voltage, current and displacement during isotonic actuation of an electro-ribbon actuator. (F) Manufacture of standard electro-ribbon actuators. (G) Photographs of standard electro-ribbon actuator, which is made from thin steel electrodes and polyvinyl chloride (PVC) tape: plan-view and lifting a 20 g mass. Scale bars indicate 10 mm.

Fig. 2. Electro-ribbon actuator characterisation. (A), Isometric tensile force at 0.1 mm actuator extension. Inset photographs show electro-origami zipping. (B), Isometric tensile force at an applied voltage of 6 kV, with inset diagrams showing extension state. Points in (A) and (B) are averages of 5 trials for one sample and error bars show standard deviation between trials; inter-sample variance was low (Fig. S4D–E). (C), Bandwidth testing, showing full-amplitude contraction at 0.125 Hz and partial-amplitude oscillation at 5 and 10 Hz respectively. (D), Cyclic testing over 100 thousand cycles. (E), Voltage, current and electrical power traces during an experiment to measure efficiency. (F), Mechanical power output testing. The peak and average specific power were 103.51 W kg⁻¹ and 51.45 W kg⁻¹ respectively. (G, H, I), Electro-ribbon actuator maximum stroke and load lifted variation with electrode thickness, length and width respectively. Scale bars indicate 10 mm.

Fig. 3. Electro-ribbon actuators made with different stiffness and from different materials. (A), A high-stress actuator lifting 410 g. (B), A high-stroke actuator lifting 10.75 g. (C), Electro-ribbon actuator made from indium–tin–oxide (ITO) coated polyethylene terephthalate (PET) lifting a 5 g mass. (D), A 3D printed electro-ribbon actuator, featuring 3D-printed graphene-loaded polylactic acid (PLA) conductors and a 3D-printed pure PLA insulator. (E) Electro-ribbon actuator made from pencil and paper lifting a 3 g mass. Scale bars indicate 10 mm.

Fig. 4. Electro-ribbon actuators integrated into multi-actuator structures. Series (A) parallel (B) and lattice (C) configurations of electro-ribbon actuators. Scale bars indicate 20 mm.

Fig. 5. Other electro-origami actuators. (A), Pre-bent electro-ribbon actuator that does not require pre-loading before actuation. (B), Electro-origami spiral that wraps around itself when actuated. (C), Electro-origami actuator inspired by spider silk, spooling around

a central cylinder in the same way that spider silk spools around liquid droplets (inset photographs kindly provided by authors of (31)). Scale bars indicate 20 mm.

Fig. 6. Electro-origami devices. (A), Multifunctional electro-origami design, which can be used to make four unique functional devices. (B), Electro-origami solenoid actuator. (C), Electro-origami adaptive gripper, which also benefits from electro-adhesive forces. (D), Electro-origami cilium structure, which drives a beam tip along a ciliate motion path. (E), Electro-origami locomotion robot, which can move left or right depending on the direction of sequential electrode charging. (F), Electro-origami fan that closes when activated. (G), Electro-origami muscle inspired by paper springs. (H), Electro-origami crane that flaps its wings when actuated. Scale bars indicate 10 mm.

Table 1. Dimensions, masses, actuator contractions and descriptions of steel-PVC electro-ribbon actuators.

	Electrode length (mm)	Electrode width (mm)	Electrode thickness (μm)	Conductor and insulator* mass (g)	Actuator contraction (%)	Description
Standard	100	12.7	50	2.28	99.38	
High force	100	12.7	1000	25	23.93	Actuator force: 12.91 N
High stress	10	12.7	100	0.9	33.91	Stress: 40.77 kPa
High contraction	200	12.7	20	2.95	99.84	Contraction: 99.84%
High contraction rate	100	12.7	500	13.2	81.48	Average contraction rate: 1161% s ⁻¹ Peak contraction rate: 1985% s ⁻¹
High specific force	10	12.7	50	0.36	17.05	Specific force: 10164.25 N kg ⁻¹
High specific energy	100	12.7	50	2.28	99.38	Specific energy: 6.8809 J kg ⁻¹
High specific power	100	12.7	500	13.2	81.48	Average specific power: 51.45 W kg ⁻¹ Peak specific power: 103.51 W kg ⁻¹
High energy density	10	12.7	50	0.63	68.97	Energy density of 44.17 kJ m ⁻³
High power density	100	12.7	500	13.2	81.48	Average power density 424.45 kW m ⁻³ Peak power density 853.83 kW m ⁻³
Pre-bent	70	12.7	70	2.24	96.30	

* In all electro-ribbon actuators, the insulator consisted of two layers of 130 μm thick PVC tape